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Interplay of seismic and aseismic deformations during earthquake swarms: an experimental approach

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Abstract

Observations of earthquake swarms and slow propagating ruptures on related faults suggest a close relation between the two phenomena. Earthquakes are the signature of fast unstable ruptures initiated on localized asperities while slow aseismic deformations are experienced on large stable segments of the fault plane. The spatial proximity and the temporal coincidence of both fault mechanical responses highlight the variability of fault rheology. However, the mechanism relating earthquakes and aseismic processes is still elusive due to the difficulty of imaging these phenomena of large spatiotemporal variability at depth. Here we present laboratory experiments that explore, in great detail, the deformation processes of heterogeneous interfaces in the brittle-creep regime. We track the evolution of an interfacial crack over 7 orders of magnitude in time and 5 orders of magnitude in space using optical and acoustic sensors. We explore the response of the system to slow transient loads and show that slow deformation episodes are systematically accompanied by acoustic emissions due to local fracture energy disorder. Features of acoustic emission activities and deformation rates distributions of our experimental system are similar to those in natural faults. On the basis of an activation energy model, we link our results to the Rate and State friction model and suggest an active role of local creep deformation in driving the

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seismic activity of earthquake swarms.

Keywords:

1. Introduction

Numerous observations of a correlation between seismic activity enhancements and slow slip transients in the Earth crust have been reported in various tectonic locations (Linde et al., 1996; Crescentini et al., 1999; Lohman and McGuire, 2007; Segall et al., 2006; Liu et al., 2007) and in geothermal areas (Bourouis and Bernard, 2007; Takada and Furuya, 2010). Also, observations of postseismic slip and aftershocks following large earthquakes are manifestations of transient deformation coupled with abundant earthquake activity (Perfettini and Avouac, 2004). A central question is whether or not these two different mechanical responses of faults, *i.e.* seismic and aseismic slip, occur on closely located zones. If they are, one expects a strong interaction between the two processes.

In some cases, the seismic signal concurrent with slow slip events is characterized as tectonic tremors or low frequency earthquakes, as observed in subduction zones (Rogers and Dragert, 2003; Obara et al., 2004; Ito et al., 2007) or in transform tectonic settings like the San Andreas Fault (SAF) (Vidale and Shearer, 2006; Nadeau and Dolenc, 2005; Shelly, 2010). The aseismic nucleation phase of mainshocks has also been related to foreshocks, as in the case of the 1999 Izmit earthquake (Bouchon et al., 2011) or the 2011 Tohoku-Oki earthquake (Miyazaki et al., 2011; Ando and Imanishi, 2011; Kato et al., 2012). Seismic events associated with aseismic slip are generally located on fault planes suggesting that they represent a dynamic shear instability on the sliding interface (La Rocca et al., 2009; Shelly et al., 2009). Geodetic inversions suggest that the aseismic motion occurs on the same fault plane as the seismic events (Lohman and McGuire, 2007). However the deformation signal recorded at the surface by GPS and/or InSAR instruments only provides a macroscopic view of the deformation process at depth. Details of the aseismic slip distribution are often lacking due to the limited resolution, unless the aseismic slip occurs at the Earth surface (Dobre and Peltzer, 2007).

The close spatial and temporal occurrence of both seismic and aseismic slip suggests a causal relation between the two phenomena. Nonetheless, the causal mechanism is not straightforward as earthquakes can both trigger

34 and be triggered by slow slip events (Du et al., 2003; Perfettini and Avouac,
35 2004). It might also be that both aseismic and seismic slip are manifestations
36 of a common deformation process. In this case, the seismic signal can be
37 seen as the signature of patches on the fault plane deforming dynamically
38 whereas the geodetic observation represents an integrated signal over all the
39 deforming sites. Therefore, the deformation on a fault plane takes place over
40 a wide range of speeds. This is supported by observations of heterogeneous
41 postseismic slip on the SAF inferred from the analysis of repeating earthquake
42 sequences (Lengliné and Marsan, 2009). The dynamic events represent the
43 high velocity tail of the slip speed distribution while its average produces the
44 observed geodetic signal.

45 The contribution of earthquakes to the total amount of slip released dur-
46 ing transient episodes is generally small (Lohman and McGuire, 2007). De-
47 spite being located on a common interface, accurate spatial location of the
48 seismic activity relative to the aseismic slip is difficult to obtain. The hetero-
49 geneity of mechanical and physical properties of the interface might control
50 the partition between seismic and aseismic slip, the interface being envisioned
51 as a collection of brittle patches (asperities) embedded in an otherwise creep-
52 ing region which accommodates slow slip (Linde et al., 1996; Lohman and
53 McGuire, 2007; Wech et al., 2009; Perfettini et al., 2010). The concentration
54 of asperities, or brittle patches, governs the relative importance of dynamic
55 failures in the deformation process. It is also readily possible that tempera-
56 ture produces a broad scale effect on the slip partition over the interface and
57 thus constrains the transition between brittle and ductile rheology.

58 The physics of both seismic and aseismic processes is not straightfor-
59 ward as it involves a complex problem on a spatially heterogeneous medium
60 with a large number of degrees of freedom and short and long range inter-
61 actions. Several numerical models have tried to reproduce the evolution of
62 such systems but computations are extremely demanding and time consum-
63 ing and limited to only large scale heterogeneities (Kaneko et al., 2010), or to
64 the quasi-dynamic approximation (Hillers et al., 2007; Ariyoshi et al., 2011).
65 Analog laboratory experiments overcome these difficulties as space-time inte-
66 grations are performed by the deforming system without any model require-
67 ment. Here, we investigate the slow (creep) and fast (acoustic) deformations
68 produced by the propagation of an interfacial brittle-creep crack. Our exper-
69 imental setup is a much simpler configuration than that of a complex fault
70 zone system but the fundamental processes of interest, the interplay of slow
71 deformation and brittle fracture on the same heterogeneous interface, remain

72 similar. Our setup allows the simultaneous monitoring of both acoustic ac-
 73 tivity and the detailed geometrical evolution of the fracture. We show that
 74 seismic and aseismic events co-exist in the system and their activity rates are
 75 highly correlated. This suggests that seismic activity during swarm episodes
 76 is driven by the elastic loading of asperities by local aseismic deformations.

77 2. Experimental Setup

78 2.1. Sample Preparation

79 To prepare each sample, we use two transparent PMMA (poly methyl
 80 methacrylate) plates of dimensions $20 \times 10 \times 1.0 \text{ cm}$ and $23 \times 2.8 \times 0.5 \text{ cm}$
 81 (Figure 1). First, we sand-blast one surface of the narrow plate with glass
 82 beads of diameter $\phi \in [180 - 300] \mu\text{m}$. We clean the blasted plate to remove
 83 any electrically attached glass beads. Then we assemble the two plates in
 84 a stiff metallic loading cell with the blasted surface facing one of the sur-
 85 faces of the thick plate. Finally, we impose a homogeneous normal load on
 86 the assembled plates and heat the loaded sample to 190°C for 45 minutes
 87 to anneal the plates. The thermal annealing produces a cohesive interface,
 88 weaker than the bulk, along which the sample will break under load. The
 89 sand-blasting introduces random roughness to the plate surface that controls
 90 the heterogeneity of local strength along the interface. It also induces mi-
 91 crostructures on the plate surface that make the surface opaque. The newly
 92 formed block, after annealing, recovers its transparency since the contrast of
 93 the refraction index along the interface disappears (see Grob et al. (2009);
 94 Lengliné et al. (2011) for details). Interestingly PMMA exhibits a brittle be-
 95 havior at short time scales and is semi-brittle or even plastic at longer times.
 96 Macroscopically this long time scale regime is described by a ductile rheol-
 97 ogy. PMMA shows a time-temperature equivalence desirable for addressing
 98 either high temperature processes or very long term evolution (Ward and
 99 Hadley, 1993). This richness of the PMMA rheology enables the observation
 100 of a brittle-creep rupture regime. It provides an attractive analogy for the
 101 study of numerous time-dependent mechanisms in the Earth crust as those
 102 originating at the brittle-ductile transition.

103 2.2. Mechanical loading

104 Once the sample is ready, we clamp the widest PMMA plate to a stiff
 105 aluminum frame. A stepping motor applies the loading over the top side
 106 of the narrow plate in a direction normal to the plate interface (Figure 1).

107 We measure the vertical displacement of the loading point with a linear
 108 variable differential transformer (LVDT) with a resolution of $1.3\,\mu\text{m}$. The
 109 vertical displacement imposed on the narrower plate induces stable mode I
 110 propagation of a planar fracture along the prescribed weak interface. We
 111 impose a variation of the loading speed, $\dot{u}(t)$, to simulate a variation of
 112 the external driving force. We performed 14 experiments where we applied
 113 various forms of temporal transients, namely a step increase, a bump increase
 114 and a sinusoidal of the loading speed imposed by the stepping motor. All
 115 these transient loads produced broad scale variation of the front speed (e.g.
 116 Figure 2, see also Supplementary Material) and they could be interpreted as
 117 an analog for far field stress perturbations caused, for example, by pore fluid
 118 pressure, magmatic intrusion or mantle flow.

119 *2.3. Optical events*

120 We monitor the fracture front propagation using a fast camera (Cam-
 121 Record 600) with up to 1000 fps or a slow speed camera (Nikon D700) with
 122 up to 5 fps to follow the progression of the front position over longer time
 123 scales (Figure 1). Optical images of the interfacial rupture show dark and
 124 bright regions corresponding to open crack and unbroken parts of the sample
 125 respectively. Image processing determines the transition between dark and
 126 bright areas that defines the fracture front. We first compute the difference
 127 between each image and the first image of the experiment. The image differ-
 128 ence highlights the fracture front while removing permanent artifacts. Then,
 129 grayscale images are transformed into black and white images according to a
 130 gray level threshold separating bright and dark regions. Then, we calculate
 131 the gradient in the direction of front propagation to highlight the transi-
 132 tion zone. We finally extract connected pixels from the gradient images that
 133 correspond to the front position, $a(x, t)$. The front propagates along the y
 134 axis with the origin defined at the loading point and is positive in the direc-
 135 tion of crack propagation. The x axis is perpendicular to y and defines the
 136 coordinate of a point along the front and $\bar{a}(t)$ is the mean position of the
 137 front at time t (see Måløy et al. (2006) and Grob et al. (2009) for details).
 138 We compute the local speed of the crack as the pixel size divided by the
 139 time spent by the front in each pixel (Figure 3). We extract the pixels with
 140 the highest speeds from the local movements of the front. The broad scale
 141 variation of the front velocity could be compared to slow events recorded by
 142 geodetic instruments in a tectonic context. The patches of higher than av-
 143 erage deformation speed could be considered as analogous to local creeping

144 episodes or slow slip events. They represent slow deformation episodes that
 145 locally exceed the macroscopic deformation rate. We follow the procedure
 146 detailed by Grob et al. (2009) to define such events. We define an “optical
 147 event” (OE) as a as a cluster of connected pixels which velocity exceeds a
 148 prescribed speed threshold, v_{th} . Here we adopt $v_{th} = 10 \times \langle v \rangle$, where $\langle v \rangle$ is
 149 the mean velocity of the crack during an experiment. Although these optical
 150 events have higher velocities than most of the deforming sites, they remain
 151 slow deformation episodes compared to dynamic events (the average speed
 152 $\langle v \rangle \simeq 500 \mu m s^{-1}$, far from the Rayleigh wave speed, $V_r \simeq 1.7 \cdot 10^9 \mu m s^{-1}$).
 153 These optical events are characterized by a Gutenberg-Richter power law
 154 with a slope similar to that of tectonic earthquakes (Grob et al., 2009). This
 155 Gutenberg-Richter relation might also be related to the magnitude-frequency
 156 scaling inferred for slow-slip events (Wech et al., 2010).

157 *2.4. Acoustic events*

158 The crack propagation produces acoustic activity that we monitor with
 159 a 32 elements linear array of piezo-electric sensors. Sensors are located on
 160 a line parallel to the plate axis and sensors separation is 3 mm (see Fig. 1).
 161 The typical distance between the closest acoustic sensor and the border of
 162 the plate is 1 cm. The sensors peak frequency response is ~ 500 kHz and
 163 all channels are continuously recorded at 5 MHz. For each experiment, we
 164 extract the acoustic signal recorded in the two closest acoustic sensors to the
 165 fracture front line. We manually trigger the acquisition of the acoustic data,
 166 which is synchronized with the camera time sequence. The recordings of the
 167 acoustic signals last, in our experiments, for a maximum of 50 s.
 168 We use a short-term-average to long-term-average ratio (STA/LTA) to detect
 169 acoustic events (AE) in the recorded acoustic signal (Earle and Shearer,
 170 1994). This procedure is similar to that applied to earthquake data. In our
 171 case, we use shorter time windows tailored to our short signal durations and
 172 high frequency acquisition rate. The STA window length is $20 \mu s$, the LTA
 173 window length is $100 \mu s$ and the threshold for setting an STA/LTA detection
 174 is 2.0. An event must be detected simultaneously on the two closest channels
 175 to be considered in our analysis. We show an example of the acoustic signal
 176 recorded during one experiment in Figure 4. The typical duration of the
 177 recorded events is on the order of $100 \mu s$. The performance of the detection
 178 algorithm is illustrated in Figure 5. As expected, the detection of events is
 179 associated with high amplitudes of the recorded signal on the two closest
 180 channels. AEs result from the fracturing of geometrical asperities over the

181 interface. We estimate the typical spatial scale of these failures to be less
182 than several microns (The largest AE is generated during an optical event
183 that has maximum dimensions of $\sim 600 \mu\text{m}$ by $30 \mu\text{m}$). We observe non-
184 uniformly distributed clustering of acoustic and optical activity (Figure 5).
185 The temporal coincidence of AEs and OEs is important but not systematic
186 (Figure 5). It is attributed to AEs that are too small to be optically detected,
187 OEs that are genuinely aseismic, and clusters of AEs that are lumped into a
188 single large OE.

189 3. Results

190 3.1. Distribution of inter-event time

191 Our results suggest the presence of clustering of the acoustic activity
192 (Figure 5). We quantify this clustering by calculating the distribution of
193 inter-event times of successive AEs for all 14 experiments. We only consid-
194 ered AE when the loading rate was nearly constant in order to avoid mixing
195 populations recorded during different loading rates. Inter-event times are
196 normalized by the average AE rate of each experiment (the average AE rate
197 for the different experiments, is on the order of 10^2 events/sec). The probabil-
198 ity density functions (pdf) for all the experiments are well approximated by
199 a gamma function (Figure 6). The displayed gamma distribution is obtained
200 from averaging the parameters of each individual fit. Figure 6 also includes
201 the inter-event time distribution for the ISC worldwide catalog for earth-
202 quakes with magnitude $M > 5.5$ in the period 1975-2004. Temporal clustering
203 has been well documented for earthquakes and is suggested to be a result of
204 interactions among earthquakes (Corral, 2004; Molchan, 2005; Hainzl et al.,
205 2006; Saichev and Sornette, 2007). The normalization of the interevent time
206 is obtained similarly by the average seismic event rate (on the order of 1
207 event/day). The good agreement between the gamma distribution and the
208 pdf obtained from our experimental data is similar to that for earthquake
209 data (Corral, 2004) or AE recorded during rock fracture experiments (David-
210 sen et al., 2007). It suggests that the mechanism responsible for the seismic
211 activity in fault systems or rock fractures shares strong similarities with our
212 experiment, which can be seen as an analogous system for seismicity inter-
213 actions. We interpret the decay at short time scale as the emergence of an
214 Omori-Utsu law describing interactions among events while the distribution
215 evolves to an exponential distribution representative of a Poisson process at
216 longer time scales (Saichev and Sornette, 2007).

217 3.2. Power-law distribution of local slip-rate

218 We calculate the pdf of the local velocities following Måløy et al. (2006) for
219 six of the experiments where we used the fast video camera at high sampling
220 rate. We only analyze, for these experiments, time windows with an almost
221 constant large scale velocity. The local velocity is normalized by the average
222 velocity of the crack, $\langle v \rangle$. Front velocities exhibit significant fluctuations at
223 small scales (Figure 3). For $v > \langle v \rangle$ the pdf shows a power law decay with
224 exponent 2.55 consistent with previous works (Måløy et al., 2006; Lengliné
225 et al., 2011). This power law behavior of the deformation rate at small scale,
226 in our experiment, has to be compared to the observed behavior in natural
227 fault systems. For instance, in southern California, fault slip rates are found
228 to obey such a power law scaling where the fault system is characterized
229 by slow slip rates (Meade, 2007). This comparison suggests that a second
230 relation between our experiments and natural fault behavior can be proposed
231 and that the scaling behavior is a general feature of slowly deforming media
232 in the presence of heterogeneities.

233 3.3. Lateral migration of the deformation velocity

234 Migration of the fracture velocity along the crack front direction is anal-
235 ogous to the dip-parallel slip propagation revealed by tremors in subduction
236 zone (Shelly et al., 2007; Ghosh et al., 2010). In most experiments, high
237 loading rates or low recording acquisition rates do not allow us to distinguish
238 migration patterns confidently as interactions among sites are numerous and
239 occur over short time intervals. We find indications of along-front migration
240 with tractable velocities for long enough times during experiments where
241 loading rates are the lowest (Figure 8). High velocity clusters appear in
242 streaks that suggest the progression of the rupture in the direction perpen-
243 dicular to the crack front propagation. The migration velocity of these high
244 velocity streaks is on the order of 2 cm/s (Figure 8). During this time inter-
245 val, the crack front propagated at a typical velocity of 400 $\mu m/s$. We note
246 that this migration speed is higher than the crack front speed. Taking 10-100
247 km/h as a typical range of dip-parallel tremor migration (Shelly et al., 2007;
248 Ghosh et al., 2010), and 10 km/day as an estimate of along-strike speed of
249 the slow slip event (e.g. Bartlow et al., 2011), the ratio of these two velocities
250 is in the range 25-250. The velocity ratio obtained in our experiment is on
251 the order of 50, well within the range obtained in subduction zones.

252 3.4. An interplay of seismic and aseismic local deformations

253 The evolution of the acoustic emission (AE) rate, the spatial average ve-
 254 locity of the crack front and the optical event (OE) rate are similar (Figure 7).
 255 AE, OE rates and the average front velocities are computed for intervals of
 256 0.2 s. A clear temporal relation between these three quantities at this large
 257 scale can be inferred: the AE and OE rates closely follow the macroscopic
 258 variation of crack front speed. The brittle fracture propagation generating
 259 acoustic emission and creep deformation co-exist in the same zone and are
 260 active at the same time.

261 We calculate the affine relation connecting the average front speed and
 262 the AE rate for all experiments. The residuals of the linear relation are small
 263 and symmetrically distributed suggesting a linear relation between AE rate
 264 and crack velocity. This is attested by the correlation coefficient, ρ , computed
 265 for each experiment between these two variables. The correlation coefficient
 266 is defined as $\rho = \sigma_{xy} / \sigma_x \sigma_y$, with σ_{xy} the covariance of the AE rate with the
 267 front speed and σ_x and σ_y the standard deviations of the AE rate and the
 268 front speed. The correlation coefficient, ρ for a 0.2 s window and for our 14
 269 experiments ranges from $\rho = 0.75$ to 0.97 and with a mean value of 0.87.

270 We now focus on smaller time scales relevant to acoustic activity and slow
 271 movement of the crack front. The crack front velocity shows important fluc-
 272 tuations at small scales, although being smooth and rather continuous when
 273 observed at large scale. These fluctuations result from the heterogeneous
 274 nature of the interface and the elastic interactions along the crack front line.
 275 We investigate the temporal relation between OE and AE recorded during
 276 the 6 experiments which show the highest acoustic activity and the best re-
 277 solved crack advance. The cross-correlation function, $C(\Delta t)$, between the
 278 rate of AE, $r_{AE}(t)$, and the rate of optical events, $r_{OE}(t)$ is

$$C(\Delta t) = \frac{1}{\sqrt{C_{AE}C_{OE}}} \sum_{t_0}^{t_f} r_{OE}(t + \Delta t) \times r_{AE}(t), \quad (1)$$

279 where C_{AE} and C_{OE} are the auto-correlations values at zero lag time of the
 280 AE and the OE rates, respectively. For both AE and OE, rates are computed
 281 as the number of events detected in time intervals of 5 ms from time t_0 to time
 282 t_f (the mean is removed from the time-series). The maximum correlation
 283 between the two types of signals is at zero lag time (Figure 9). It shows that
 284 the acoustic activity occurs mostly in a short time span around the aseismic
 285 deformation. The quasi-symmetric shape of the correlation function also

286 suggests that optical events both precede and follow acoustic activity during
 287 the course of an experiment highlighting the close interplay between these two
 288 modes of deformation. The slight asymmetrical shape of $C(\Delta t)$ (Figure 9)
 289 also suggests that a higher rate of OE occurs following AE than preceding it,
 290 similar to postseismic slip observed after large earthquakes (e.g. Hsu et al.,
 291 2006).

292 4. Discussion

293 In our experiments, the average fracture speed obeys the Arrhenius law
 294 at the macroscopic or global scale (Lengliné et al., 2011). Such an evolution
 295 has been inferred in numerous experimental systems reproducing slow defor-
 296 mations of rocks and other materials (Atkinson, 1984). In our experiment,
 297 this expression relates the crack front speed propagation, V , to an activation
 298 energy mechanism and can be expressed as

$$V = V_0 \exp \left(\frac{-Q}{k_B T} \right). \quad (2)$$

299 V_0 is the product of a frequency of attempt to break molecular bonds and
 300 the jump distance, k_B is the Boltzmann constant and T is the temperature.
 301 The activation energy of the process is Q

$$Q = Q_0 - G\alpha^2, \quad (3)$$

302 where Q_0 is the activation energy in the absence of applied stress, G is the
 303 energy release rate and α is the typical length scale of the atomistic fracturing
 304 process. The stress dependence in Eq. (3) is similarly often written in terms
 305 of the stress intensity factor, K , at the crack tip. It follows that by controlling
 306 the imposed loading rate on the system we modify the value of the energy
 307 release rate (equivalently stress intensity factor) at the crack tip. In this
 308 sense, simulated transient deformation processes mimic the increase of the
 309 deformation speed recorded during swarm episodes (Lohman and McGuire,
 310 2007) or slow slip events in subduction zones (Rogers and Dragert, 2003).
 311 The formulation of the crack speed in Eq. (2) has been proposed to be the
 312 physical basis of the rate and state friction model widely considered in fault
 313 mechanics (e.g. Nakatani, 2001; Rice et al., 2001). If we consider a volumetric
 314 process, the corresponding expression to Eq. (3) is

$$Q = Q_0 - \tau_c \alpha^3 \quad (4)$$

315 where the stress dependence is written in terms of the average shear stress, τ_c
316 along asperity contacts. α^3 is the activation volume of the process. Following
317 Rice et al. (2001), we call σ_c the average normal stress on contact zones,
318 defined as: $\tau_c/\sigma_c = \tau/\sigma$, with τ and σ being the large scale stresses. It
319 follows from Eq. (2)

$$V = V_0 \exp \left(\frac{-Q_0 + \tau_c \alpha^3}{k_B T} \right) \quad (5)$$

320 leading to:

$$\tau = \sigma \left[\frac{Q_0}{\alpha^3 \sigma_c} + \frac{k_B T}{\sigma_c \alpha^3} \ln \left(\frac{V}{V_0} \right) \right] \quad (6)$$

321 where V is interpreted in terms of slip rate on the fault plane. Eq. 6 has
322 a similar form to the empirical relation of the rate and state friction model
323 with $a = k_B T / \sigma_c \alpha^3$ and the state dependent variable represented by $Q_0 / \alpha^3 \sigma_c$
324 (Rice et al., 2001). It follows that the progressive evolution of the front
325 position in our system can be viewed as a similar mechanical problem to the
326 evolution of slip on a fault plane with the same constitutive equation. The
327 quasi-static evolution of an anti-plane shear rupture is governed by similar
328 formulations to mode I fractures (Gao and Rice, 1986; Schmittbuhl et al.,
329 2003). Thus, we consider our mode I fracture problem analogous to shear
330 ruptures. Therefore our experimental setup is relevant for addressing the
331 mechanics of simplified fault models as studied numerically by Gao et al.
332 (1991); Perfettini et al. (2003). Provided this analogy, the crack front advance
333 $a(x, t)$ is analogous to the slip along fault $\delta(x, t)$. However each point of the
334 interface that breaks is completely unloaded due to the geometry of our
335 experimental setting. Therefore, we have no repeating failure of the same
336 patch contrary to natural faults and AE stress drops are total. However,
337 earthquake stress drops are usually a small fraction of the total stress (e.g.
338 Kanamori, 1994). Nevertheless, in both systems, AE and earthquake still
339 represent a dynamic failure mode, which makes them comparable. Following
340 the approach presented by Dieterich (1994), we propose to relate the AE rate
341 to the stress history of our system. We assume an interface composed of a
342 population of sources that generate AE. We hypothesize that the duration
343 of nucleation of these sources is longer than the duration of stress variations
344 imposed to the system. Hence, the seismicity rate, R , varies exponentially
345 with the shear stress change $\Delta\tau$ imposed on the system (Dieterich, 1994;

346 Beeler and Lockner, 2003; Cochran et al., 2004; Helmstetter and Shaw, 2009),

$$R = r \exp \left(\frac{\Delta \tau}{a \sigma} \right) \quad (7)$$

347 where r is a reference seismicity rate. The analogy mentioned above between
348 shear stress τ and the energy release rate G , suggests that in our experiment:

$$R = r \exp \left(\frac{\alpha^2 \Delta G}{k_B T} \right), \quad (8)$$

349 Notice that Eq. (8) is the same expression of that for the speed of the
350 crack as a function of G obtained by combining Eq. (2) and (3): $V =$
351 $V_0^* \exp(\alpha^2 G / k_B T)$ with $V_0^* = V_0 \exp(-Q_0 / k_B T)$. Therefore we have a di-
352 rect linear relation between AE rate R and speed of the crack V : $R \propto V$,
353 (Figure 7). At the system size, this relation provides a link between acoustic
354 activity and periods of high deformation. At smaller scales, the same mech-
355 anism is applicable as the acoustic activity is influenced by local important
356 deformations episodes (OE) (Figure 9). Such local creeping episodes are sim-
357 ilar to the small localized creep events observed on the San-Andreas fault by
358 Scholz et al. (1969).

359 We emphasize that the deformation recorded at the surface of the Earth
360 during transient episodes should be viewed as the macroscopic integration of
361 sequences of creep events. On large spatial scales, the creep events formed the
362 observed large scale behavior and correspond to the macroscopic observation
363 of the transient slip speed variation. Such a view is similar to the concept
364 developed by Scholz et al. (1969) where the deformation is modeled as the
365 integration of discrete sites subject to time-dependent strength. The acous-
366 tic deformation being recorded only represents the part of the deformation
367 corresponding to zones that fail dynamically. This model is fully compatible
368 with our observations. We also remark that sites do not fail independently
369 as attested by the local close temporal activity between creep events and
370 acoustic events. As proposed by Scholz et al. (1969), it is readily possible
371 that creep events recorded at our experimental scale are also formed of small
372 acoustic events such that down-scaling might exist up to the microscopical
373 level associated with the discrete breakage of single molecular bonds.

374 5. Conclusion

375 We analyze the coupled evolution of acoustic activity and slow defor-
376 mation during the propagation of brittle-creep fractures in a heterogeneous

medium. Our unique experimental setup addresses the relation between seismic and aseismic slip along natural faults. It provides an original characterization of slow deformation processes which are difficult to capture on faults at depth. Numerous statistical features of the deformation observed in natural systems are reproduced by our experiments like the gamma distribution of interevent times and the power law distribution of slip rates. We show that the acoustic activity (dynamic events) is part of the deformation process and it occurs over a widely distributed range of speeds including slow slip. Also, small scale observations of the deformation reveal coexistence between creep and acoustic events in the same mechanical system. The small scale complex dynamics lead to a macroscopic integrated signal of the deformation that shows a smooth and continuous deformation speed that correlates with the rate of acoustic events.

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Figure 1: Left: Side view of the experimental setup. The bottom plate is separated from the upper one using a loading force applied by a rod connected to a stepping motor. The upper PMMA plate is attached to a stiff aluminum frame (short dashed lines). The load causes a deflection u of the bottom plate and the propagation of an interfacial crack. The crack front is located at distance \bar{a} from the loading point. The front advance is monitored by a high or slow speed camera set in vertical position, perpendicular to the crack plane. Right: detailed bottom view of the sample and the loading axis. The dark gray zone corresponds to the cracked zone. The multiple black areas show the acoustic sensors of the linear array.

Figure 2: Evolution of the loading force (red), and the loading displacement (blue) during an experiment. The crack is supposed to start moving at $t = 45s$ as evidenced by the force peak. The black box on the top figure represents a zoom displayed on the bottom figure. A transient variation of speed is superimposed to a constant loading displacement rate between $t = 65s$ to $85s$ (the black line corresponds to the average front position). Camera and acoustic time windows are displayed respectively as dark gray and light gray shaded areas.

Figure 3: **A:** Map of the local speeds of the front. Image scale is given by the length of the vector showing the front propagation direction which is 1.3 mm long. The front propagates from bottom to top. We observe small scale fluctuations of the crack front speed. Black dots represent hypocenters of optical events obtained after thresholding the velocity map and are displayed at the centroid of the corresponding high velocity cluster. **B:** Zoom on a subzone of the interface located in the black rectangle in **A**. **C:** Probability density functions (pdfs) of the local velocities computed for 6 experiments. We observe a power law decay of the pdfs for $v > \langle v \rangle$ with an exponent $\nu = -2.55$ compatible with Måløy et al. (2006).

Figure 4: Example of recorded signal of an acoustic event (AE). We observed a modification of the frequency content associated with the arrival of the AE wave train. The duration of the AE on the displayed channel is around $100\mu s$. Sampling rate is 5 MHz

Figure 5: Acoustic records of two channels during 100 ms. We observe on these two channels an abundant activity as attested by the numerous peaks in the acoustic signals. Stars mark the identification of events after automatic processing of the two signals by a STA/LTA procedure and matching common detection. Rate of optical events recorded during the same time period is plotted in red.

Figure 6: Distribution of normalized inter-event time for all experiments. Each experiment is represented by a different colour. The best gamma distribution fitting all the experiments, is represented by a black curve: $p(\tau) = C\tau^{\gamma-1}e^{-\tau/\beta}$, where $C = 0.44$, $\beta = 1.8$ and $\gamma = 0.54$. Black filled diamonds show the inter-event time distribution computed from the ISC worldwide catalog for earthquakes with magnitude $M > 5.5$.

Figure 7: Evolution of the rate of AE (purple diamonds), of the average crack front speed (blue squares) and of the optical event (OE) rate (red circles) as a function of time. Rate are computed for interval of 0.2 s for a time period encompassing the loading transient shown in Figure 2. We observe that the rates of AE and OE are well correlated with the variation of the crack front speed at this broad time scale.

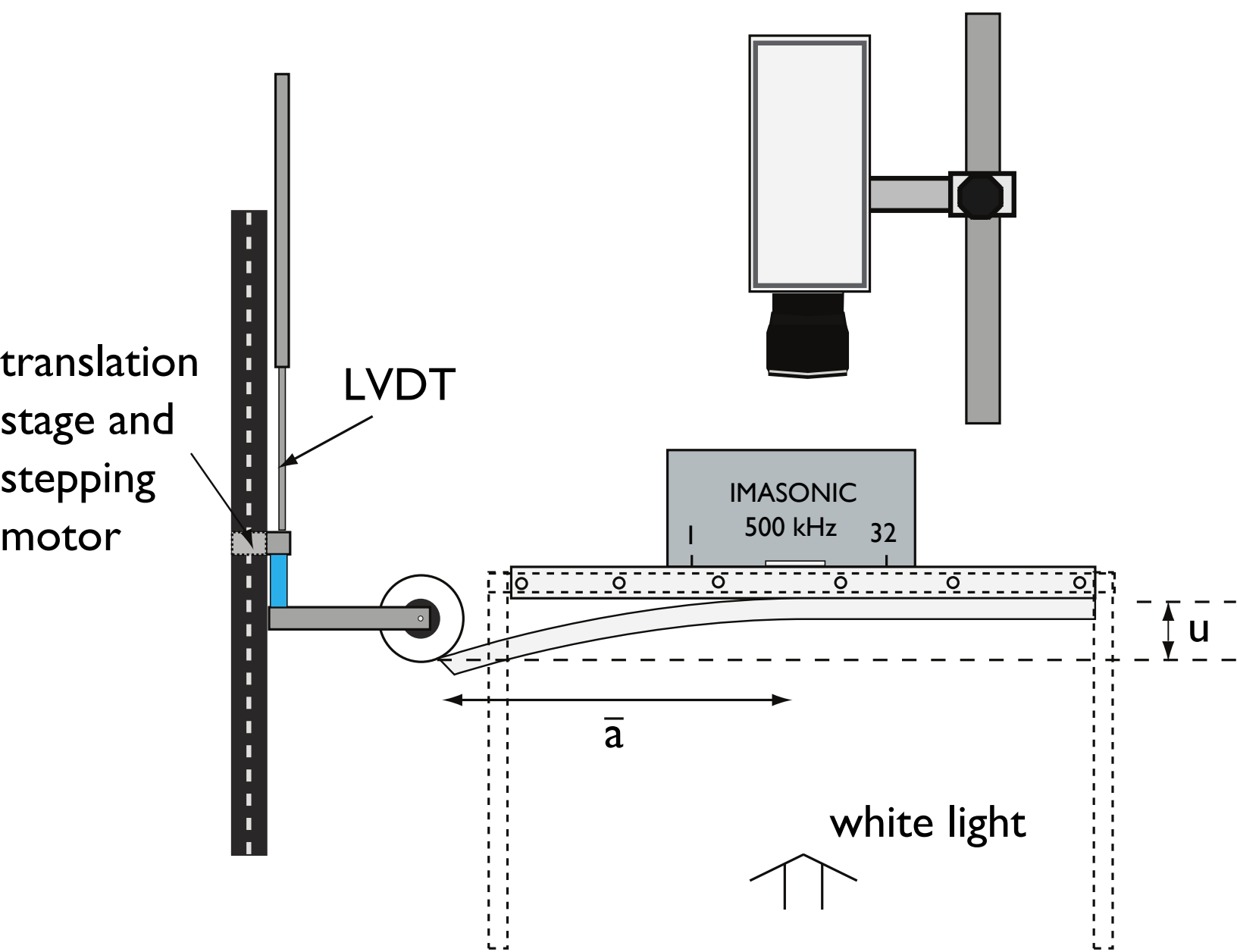
Figure 8: Top: Crack front speed as a function of time and position along front during one experiment. High velocities appear as streaks that extend along the crack front direction. Bottom left: zoom that corresponds to the space time domain delimited by the black rectangle in the upper figure. White dashed lines show the migration during two high velocity episodes. Slope of these lines gives an estimated migration speed of the order of 2 cm/s.

Figure 9: Cross-correlation function $C(\Delta t)$ between the rate of acoustic events (AE) and the rate of optical events (OE). AE rate and OE rate are computed as the number of events during intervals of 5 ms and mean is remove from the time-series. The cross-correlation function corresponds to an averaged function computed over 6 experiments. We observe that the maximum of the correlation function is found at zero time lag. We also notice the increase of the correlation function around the peak, suggesting that OE are clustered in time for some duration before and after an AE. The inset figure shows the normalized autocorrelation functions for the AE (black curve) and the OE (gray curve). Both functions show some increase around zero time lag supporting the interplay between these two modes of deformation.

*Highlights

- > We build an original experiment designated to study the relation between slow and dynamic deformations in the brittle creep regime.
- > We observe numerous acoustic events in relations with local creeping episodes.
- > In relation with faulting processes, we propose that earthquake swarms are driven by local slow slips.

Figure 1a
[Click here to download Figure: fig1a.eps](#)



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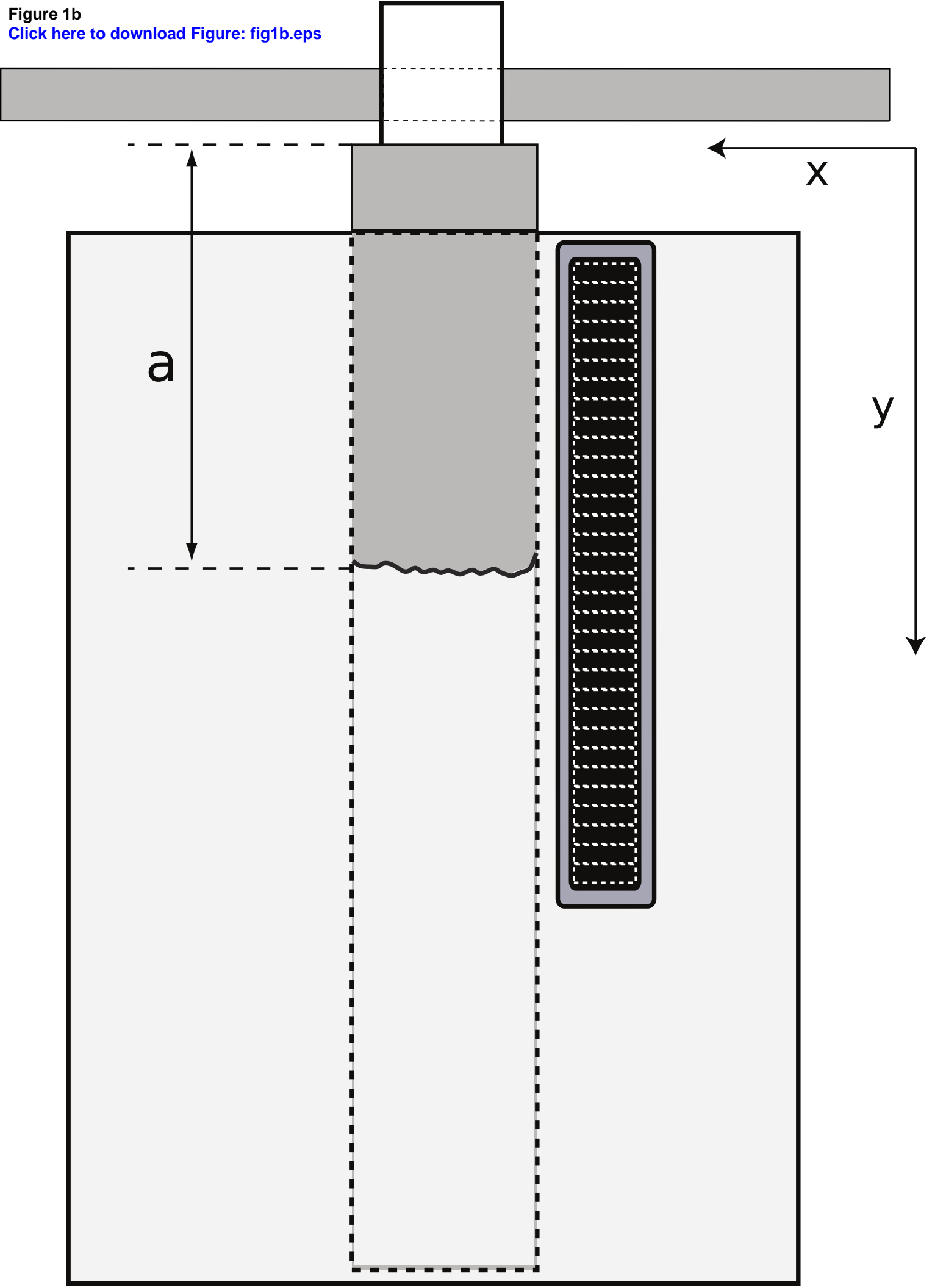


Figure 2
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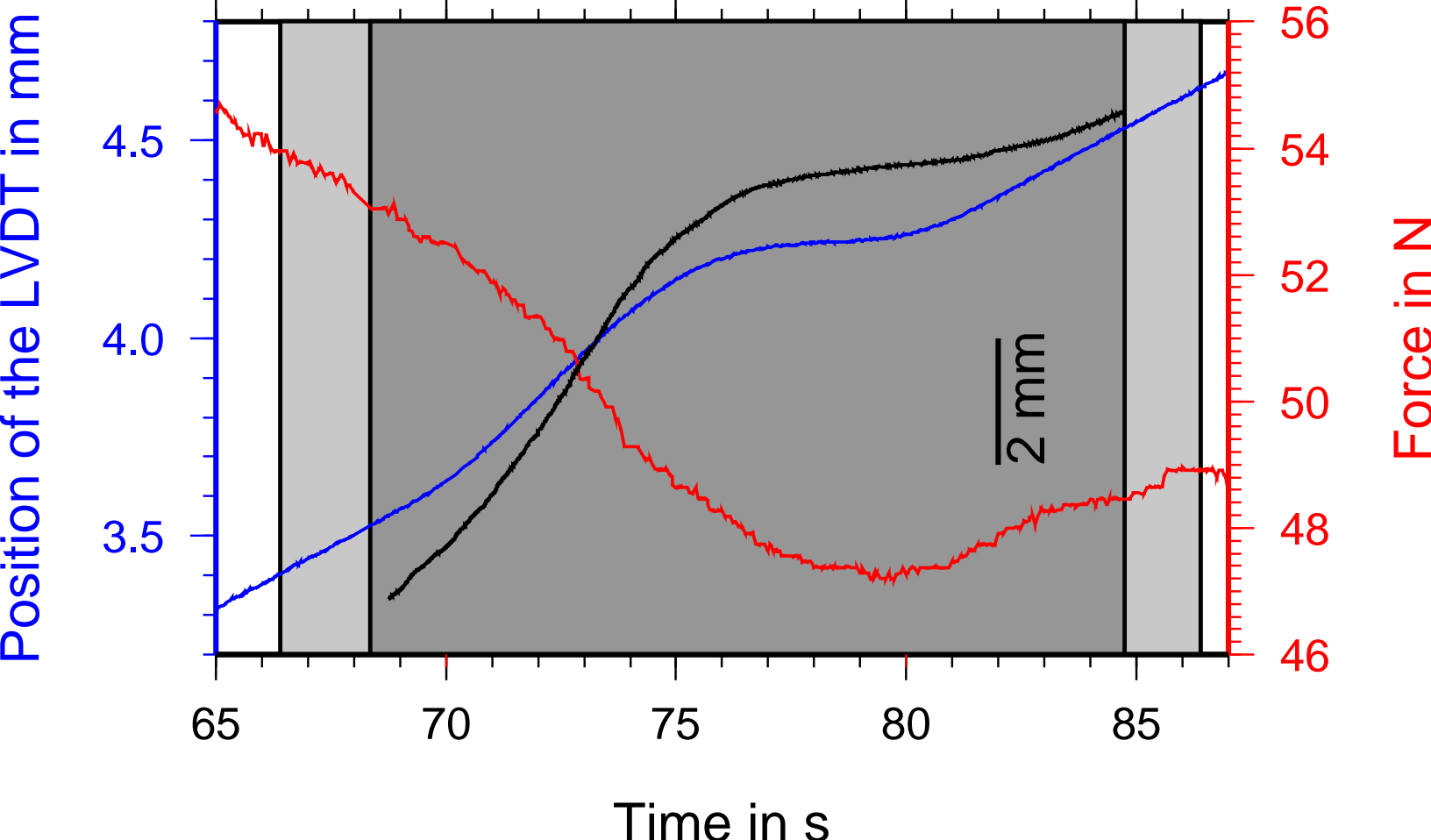
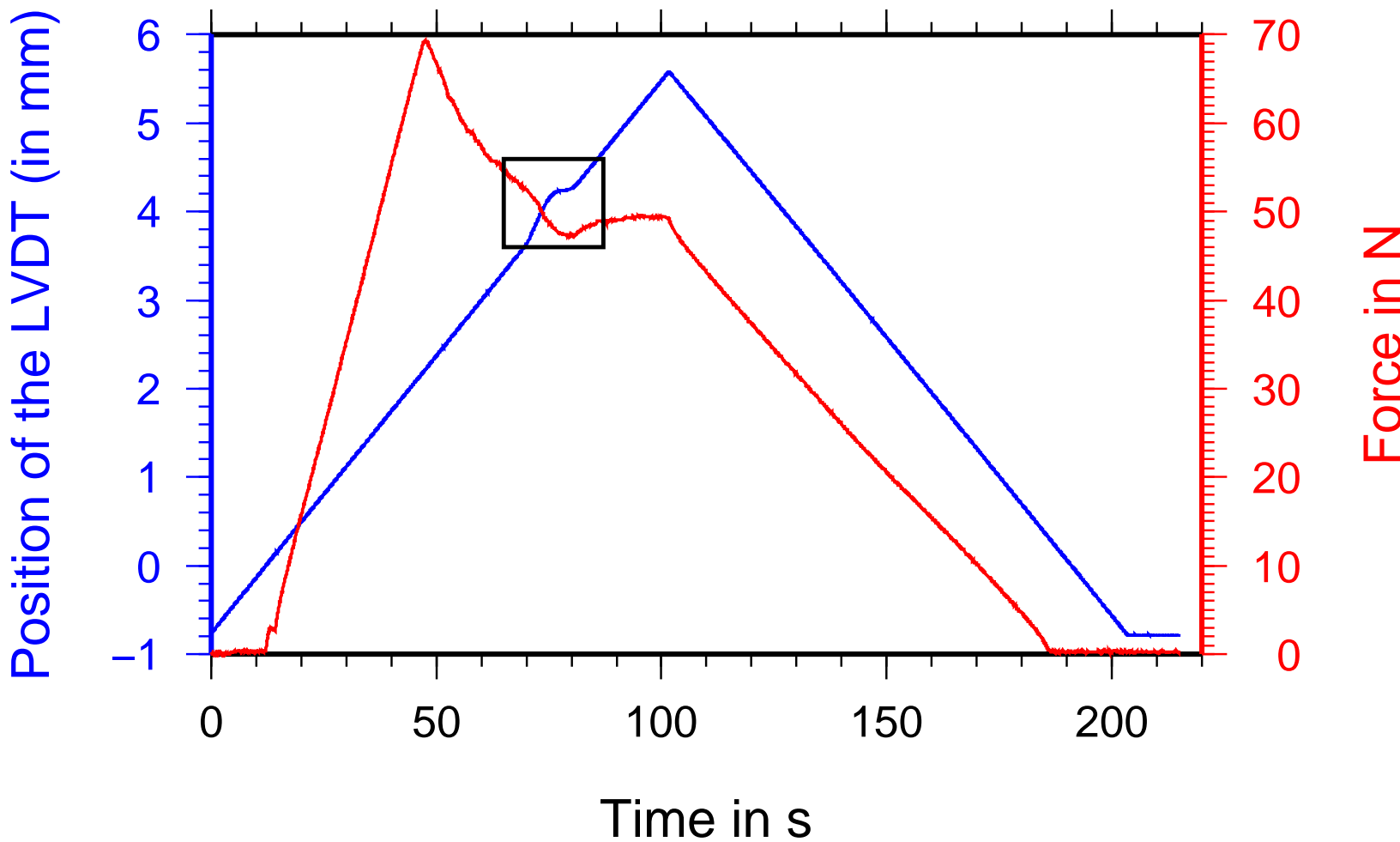


Figure 3
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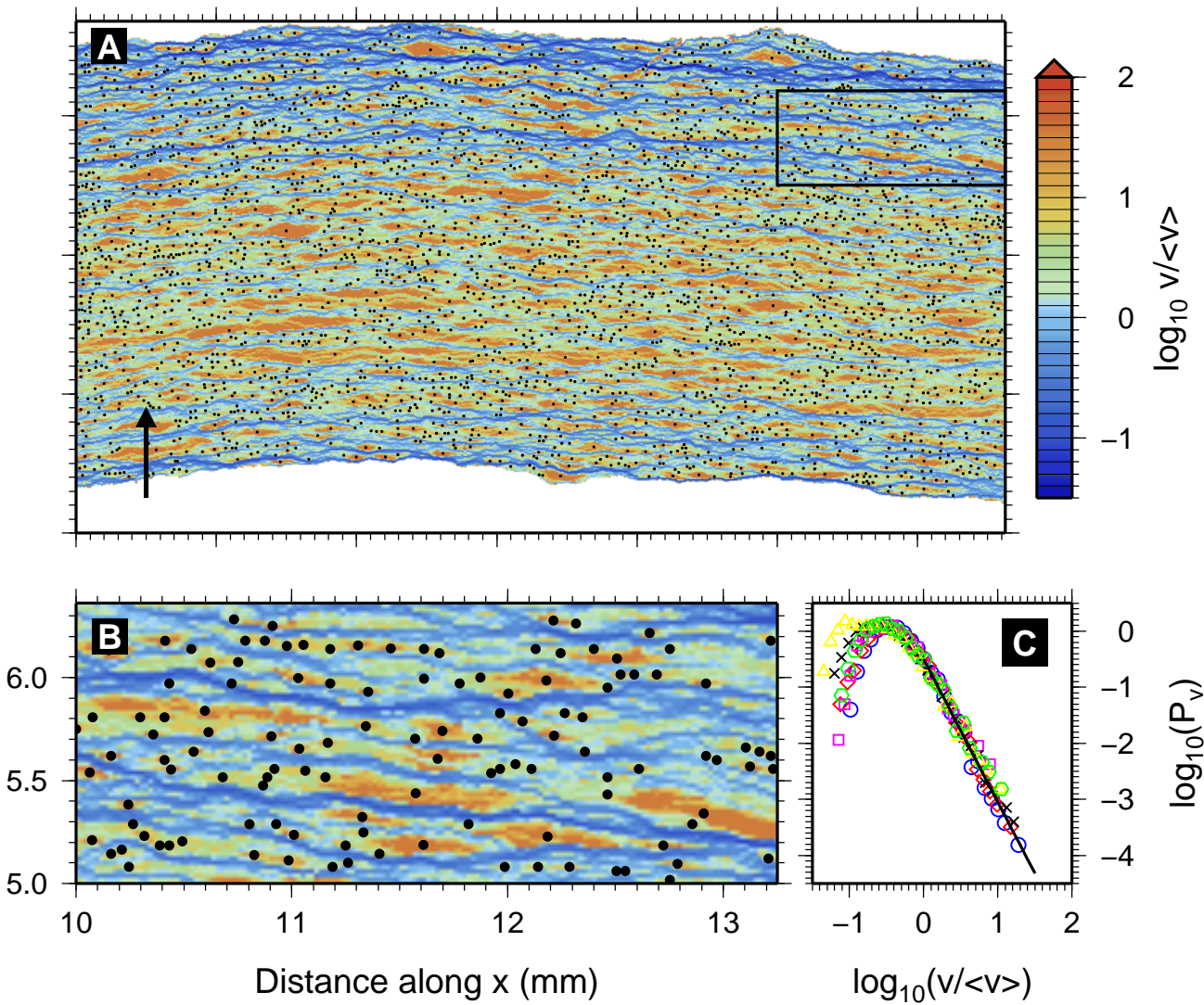


Figure 4
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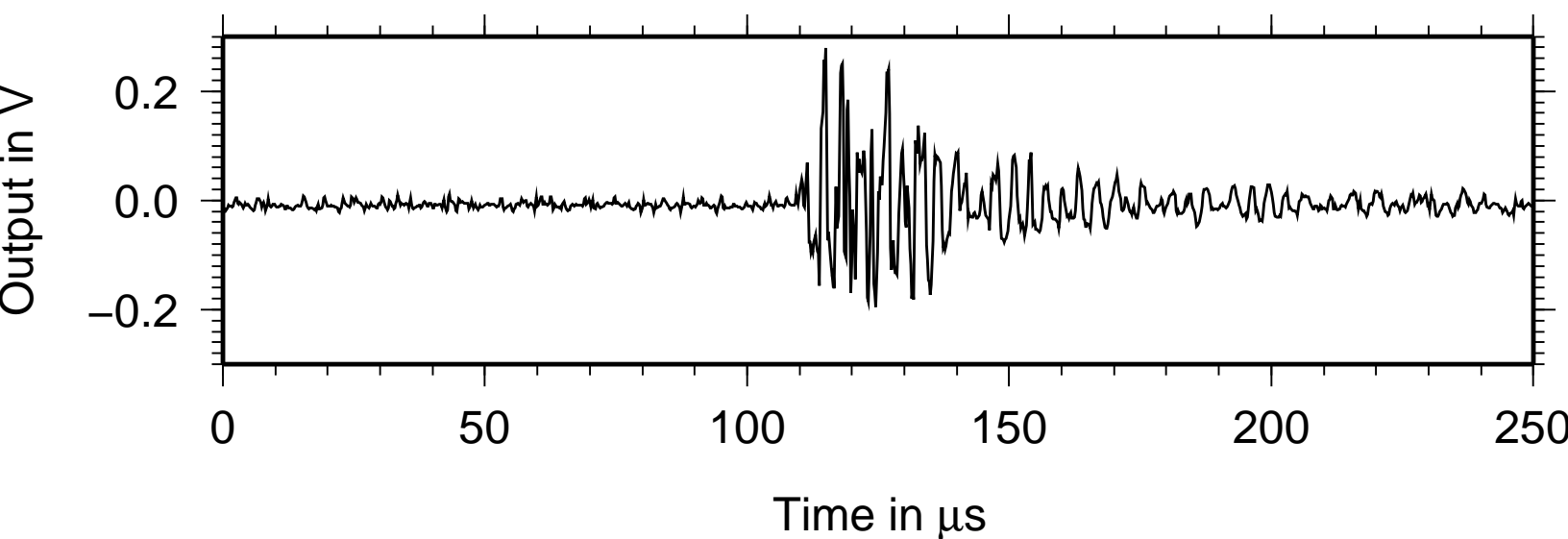
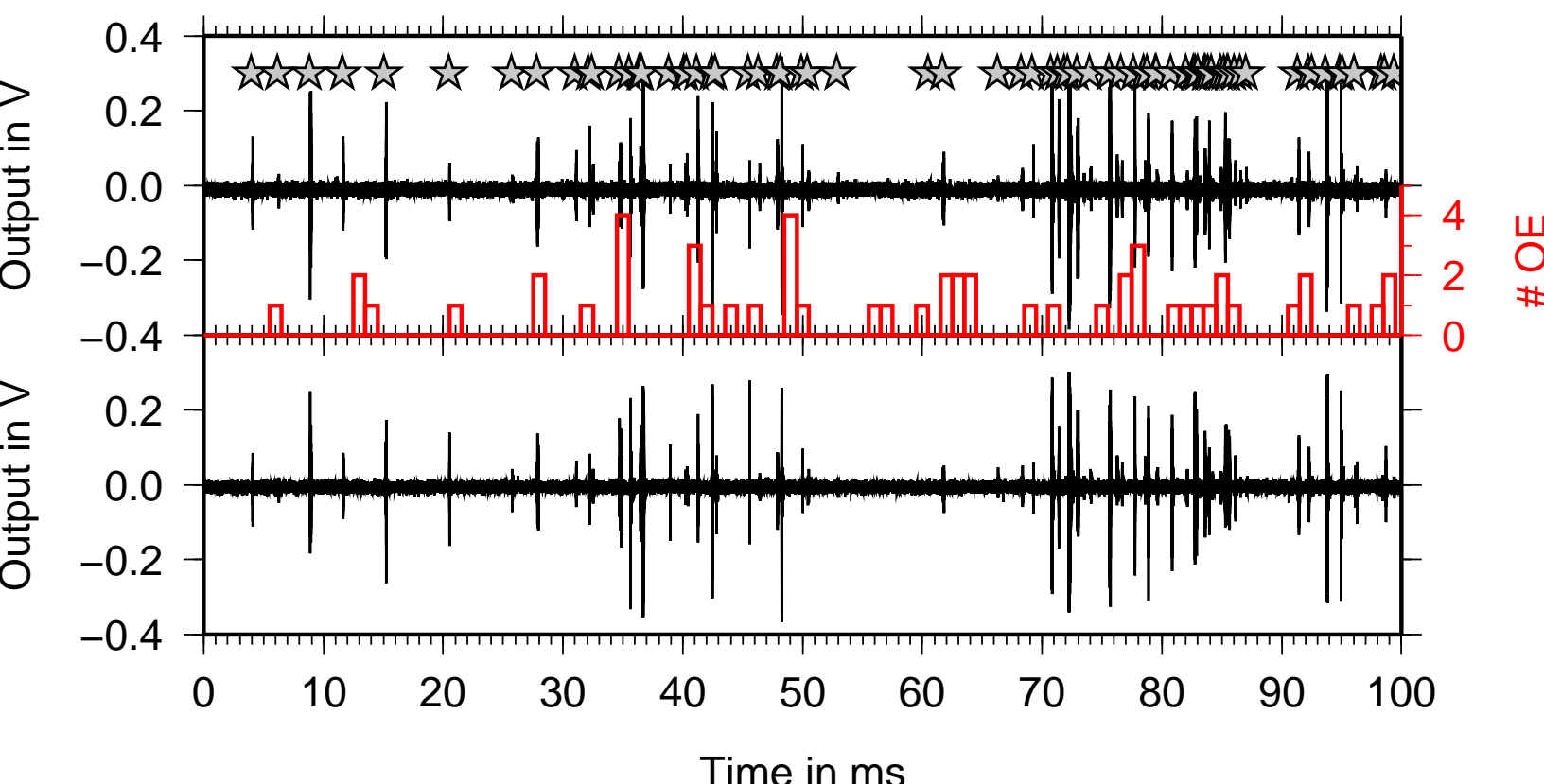


Figure 5
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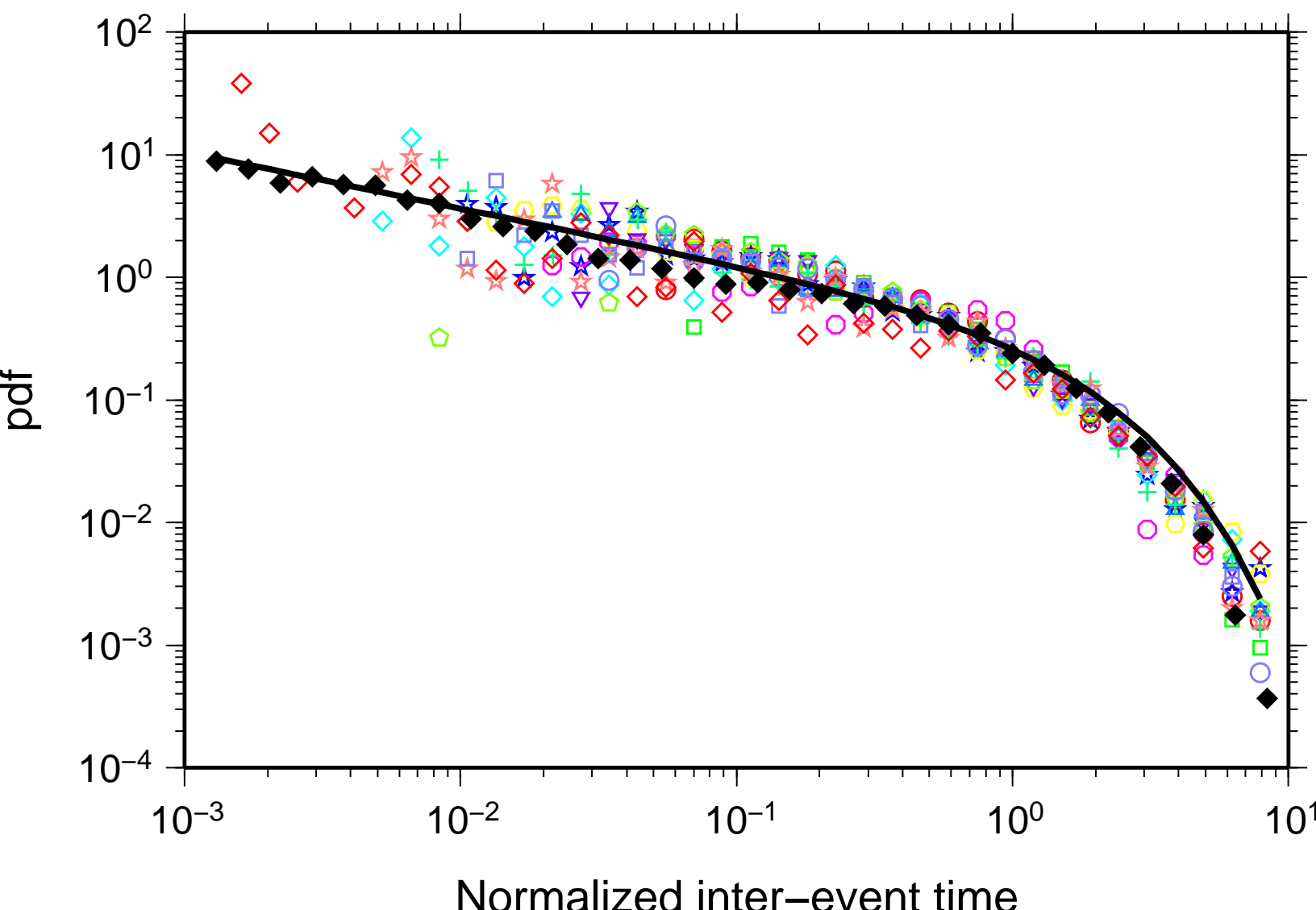


Figure 7
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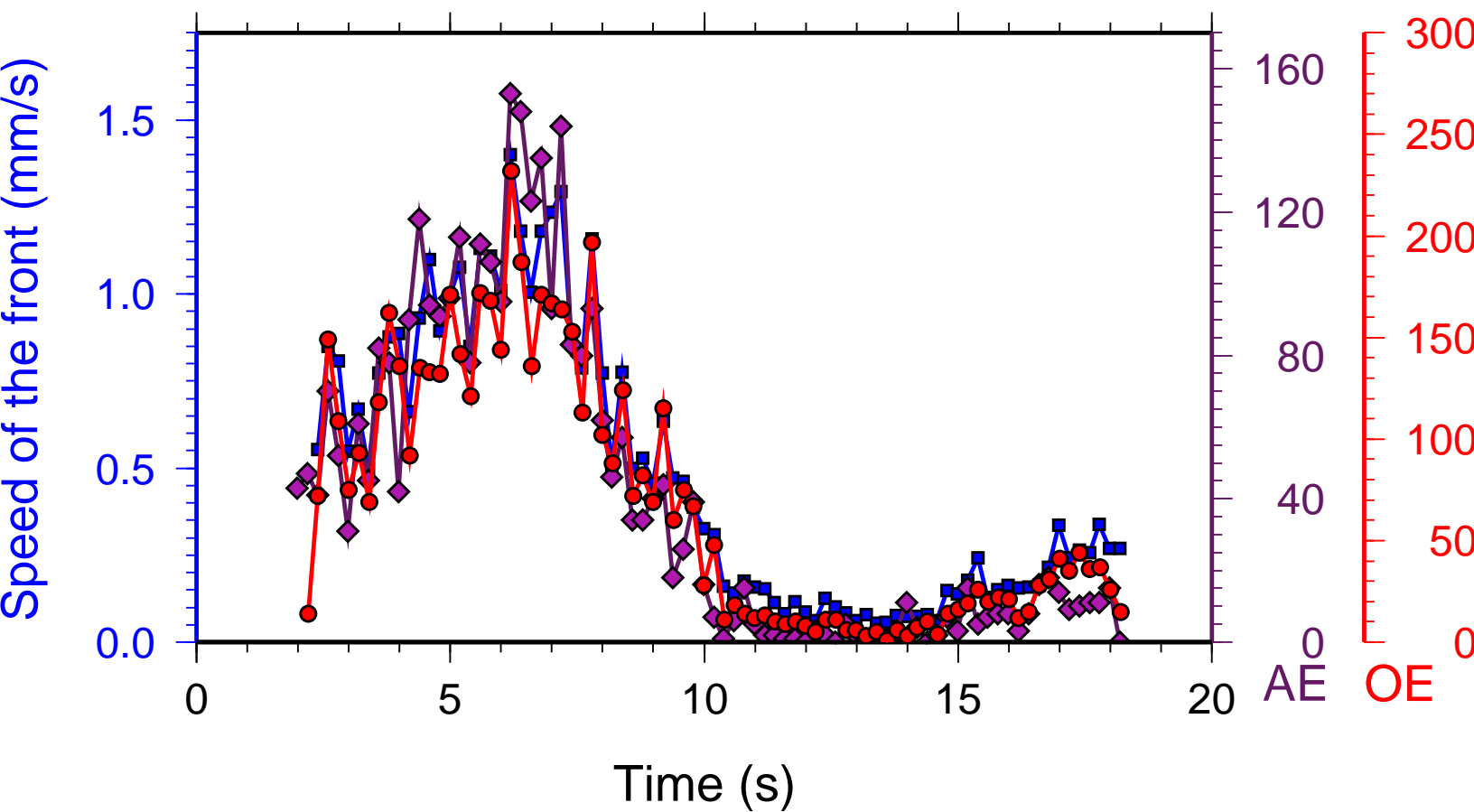


Figure 8
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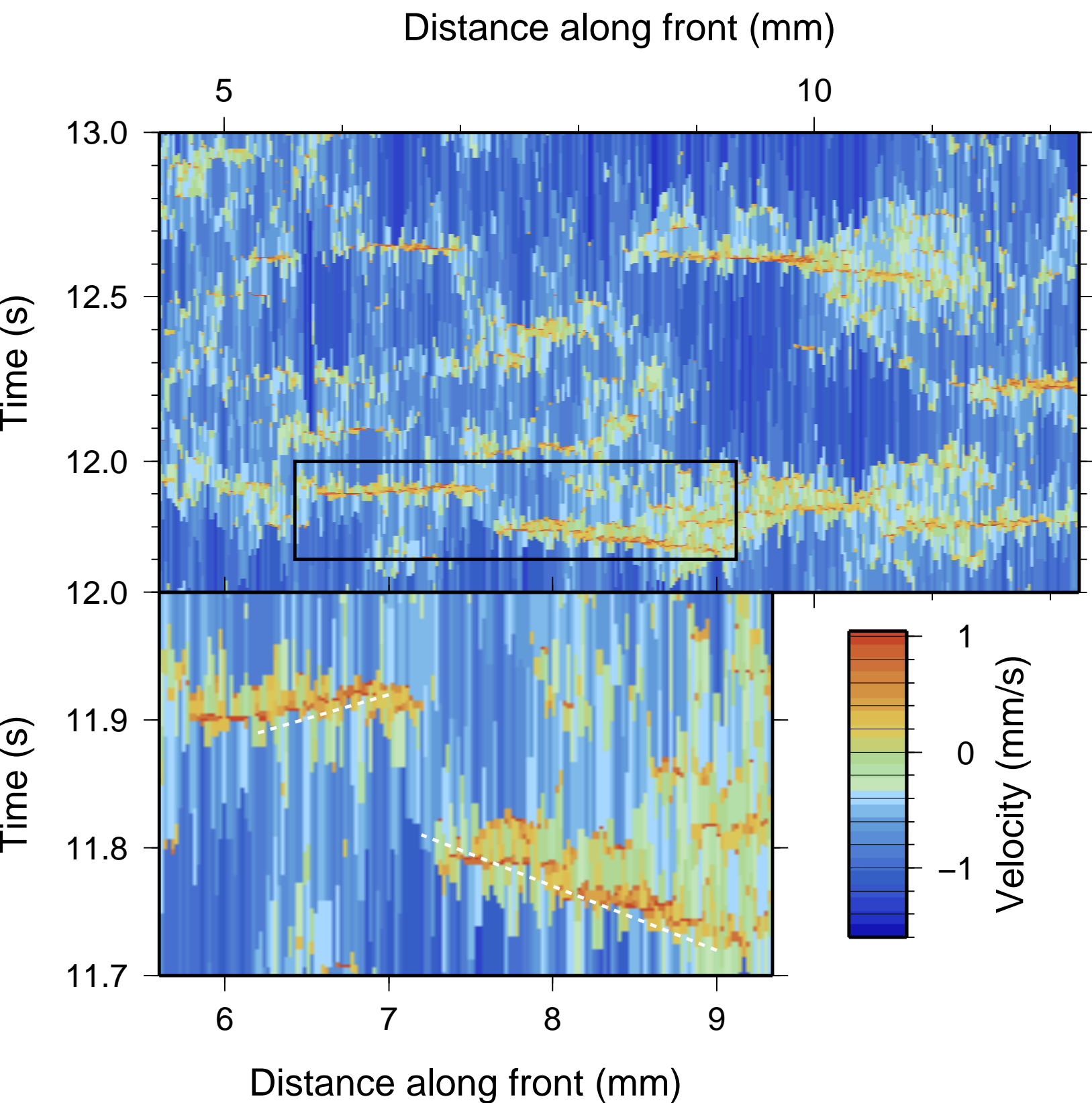
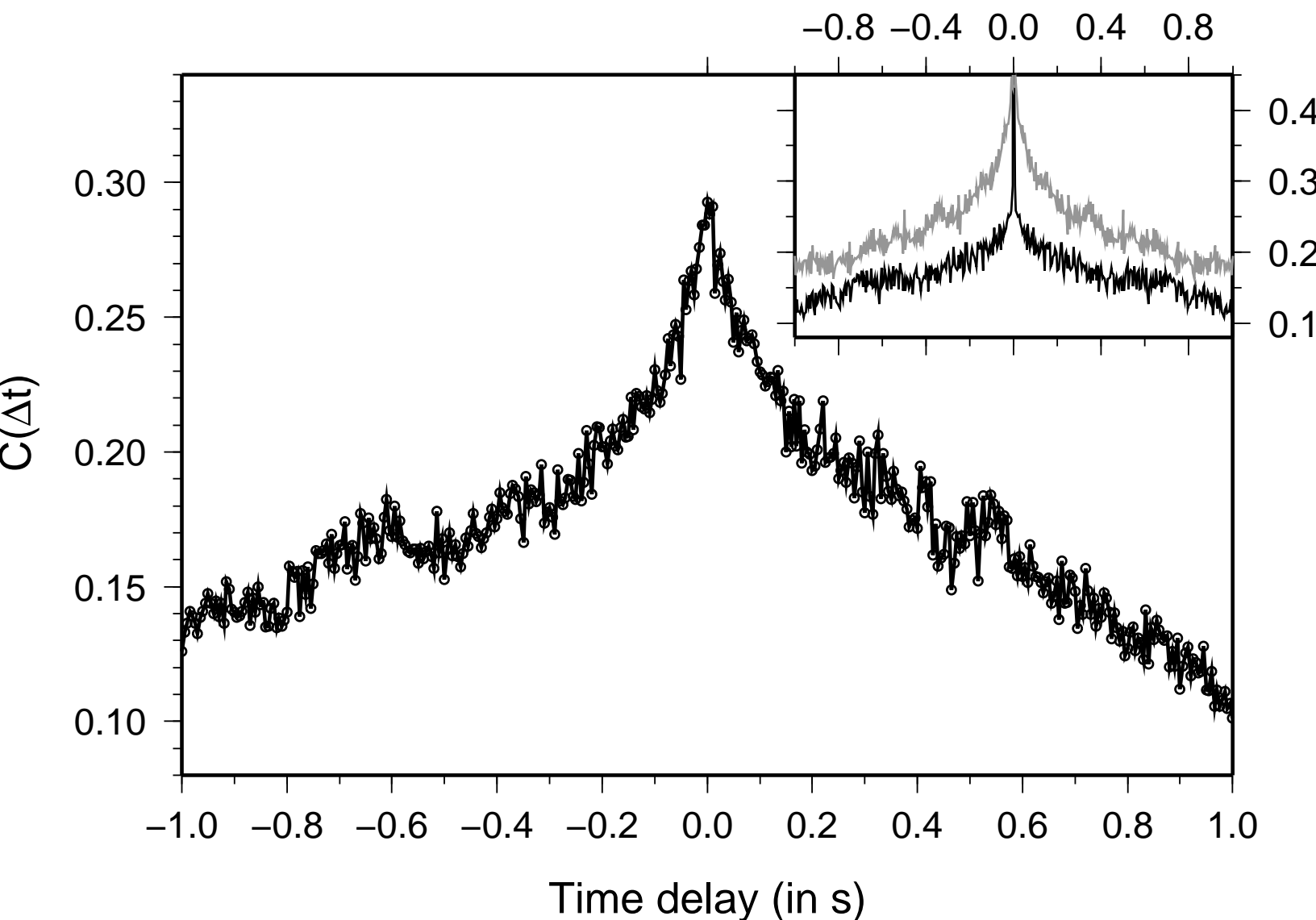


Figure 9
[Click here to download Figure: fig8.eps](#)



Supplementary material (Table I)

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